REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 074-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 1993	Final report, 1993

4. TITLE AND SUBTITLE
Calculation of Atmospheric Cooling Rates Using MODTRAN2

5. FUNDING NUMBERS
N/A

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER
N/A

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

SERDP
901 North Stuart St. Suite 303
Arlington, VA 22203

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
N/A

11. SUPPLEMENTARY NOTES
Final report for Graduate Student Research Program, Phillips Laboratory, September 1993. This work was supported in part by USAF Office of Scientific Research, Bolling AFB, Washington, D.C.

12a. DISTRIBUTION / AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
Approved for public release: distribution is unlimited	A

13. ABSTRACT ***(Maximum 200 Words)***

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14. SUBJECT TERMS	15. NUMBER OF PAGES
atmospheric cooling rates, MODTRAN2, SERDP	14
	16. PRICE CODE N/A

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
unclass	unclass	unclass	UL

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Final Report for:
Graduate Student Research Program
Phillips Laboratory

Sponsored by:
Air Force Office of Scientific Research
Bolling Air Force Base, Washington, D. C.

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Abstract

A technique for calculating atmospheric cooling rates has been developed based on infrared radiance calculations using MODTRAN2. Comparisons with benchmark line-by-line calculations show very good agreement. The technique provides significant computational time savings associated with band models vs. line-by-line calculations.

CALCULATION OF ATMOSPHERIC COOLING RATES USING MODTRAN2

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Introduction

Accurate calculations of the transfer of radiation through the atmosphere are necessary for many climate programs. Line-by-line models such as FASCODE perform detailed computations and are considered "exact" within the limitations of the current knowledge of molecular properties such as lineshape, line mixing and interaction with foreign gases. However, the amount of time required for most calculations is prohibitive. MODTRAN2, the most current version of MODTRAN, the Moderate Resolution Atmospheric Radiance and Transmittance Model, is a band model based code which has been extensively validated against FASCODE. For a 500 cm^{-1} spectral interval with comparable vertical layering the time improvement is more than a factor of 100.

In this paper, we consider the use of MODTRAN2 to calculate clear sky, infrared cooling rates for several model atmospheres. The cooling rate results are compared to similar calculations performed with FASCODE as developed by *Clough, et al.*, (1992). The current method follows that of Clough as closely as possible so that differences in the results can be attributed primarily to the differences between the line-by-line and band models.

Radiance Calculation

The radiant energy emitted at wavenumber υ along a path with optical depth τ_υ and transmittance T_υ is given by

$$I_\nu = \int_{T_\nu}^{1} B_\nu(\theta(T'_\nu))\, dT'_\nu ,$$

$$I_\nu = \int_0^{\tau_\nu} B_\nu(\theta(\tau'_\nu))\, e^{-\tau'_\nu} d\tau'_\nu \ .$$

where B_ν is the Planck function at temperature θ,

$$B_\nu(\theta) = \frac{2h\,\nu^3}{c^2\, e^{\frac{h\nu}{k\theta}} - 1} \ .$$

Here h is Planck's constant, c is the speed of light and k is Boltzmann's constant. In the present application, MODTRAN2, a moderate resolution transmittance code, has been used to first calculate the path transmittances and secondarily, the radiances.

The version of MODTRAN used to perform the necessary computations utilizes a one term Padé approximate for the effective Planck function of the form

$$B_\nu(\tau_\nu) = [\overline{B_\nu} + (a\tau_\nu)\, B_\nu(\theta_u)]\, (1 + a\tau_\nu)^{-1}$$

where θ_u is the temperature at the nearest boundary of the layer (the upper boundary for downwelling radiance and the lower boundary for upwelling radiance), $\overline{B_\nu}=B(\bar{\theta})$ where $\bar{\theta}$ is the mean temperature for the layer ℓ. The value chosen for a is 0.2 after *Clough, et al.*, (1992). For a band model, τ_ν is an effective optical depth derived from the log ratios of the full path transmittances between adjacent layers

$$\tau_\nu=\ln\left(\frac{T_l}{T_{l-1}}\right).$$

The radiance for a single layer is then given by

$$I_{\nu;l}=(T_{\nu,l}-T_{\nu,l-1})\,B_\nu(\tau_\nu).$$

The full path radiance for a path encompassing multiple layers is found recursively where the value at each layer depends on the contribution from the previous layer, see *Clough, et al.*, (1981). Treating the ground as a black body, the boundary condition is given by

$$I_{\nu;0}=B_\nu(\theta_s)$$

Comparison of Radiance Calculations FASCODE vs. MODTRAN2

The most accurate technique for calculating atmospheric transmittance and radiances employs a line-by-line code such as FASCODE. Calculations are performed at small enough wavenumber intervals to adequately represent the location, strength and shape of each spectral line within a layer, thus justifying Beer's law for calculating the optical depth. A more detailed description is available in *Ellingson, et al.*, (1991). Due to the large number of spectral lines this is a slow and cumbersome process which is therefore impractical for most uses.

MODTRAN2 employs a two parameter band model to offer more efficient computations of the line contributions. Treatment of line tails and continua is similar for both models. The two parameters are an absorption coefficient (S/d) and a line density parameter (1/d) given by

$$(S/d) = \left(\frac{1}{\Delta\nu}\right) \Sigma S_i$$

where $\Delta\nu = 1\ \mathrm{cm}^{-1}$ and

$$(1/d) = \left(\frac{1}{\Delta\nu}\right) \left(\Sigma\sqrt{S_i}\right)^2 / \Sigma S_i .$$

S_i is the integrated line strength of line i, and the sum is over N lines whose centers are contained in a bin of width $\Delta\nu$. The transmittance, T, for the spectral bin $\Delta\nu$ is given by

$$T = \left(\frac{2}{\Delta\nu}\int_0^{\Delta\nu/2} e^{-S\,u\,b(\nu)}\,d\nu\right)^n .$$

Here $b(\nu)$ is the Voigt line shape function, u is the absorber amount, S and n are defined by the band model parameters as follows:

$$S = \frac{(s/d)}{(1/d)}$$

$$n=(1/d)\,\Delta\nu.$$

For a more detailed description see A. Berk, *et al.*, (1987).

In one specific comparison, see L. Abreu, *et al.*, (1993), MODTRAN2 was shown to be 100 times faster than a non-optimized version of FASCODE for a 500 cm^{-1} spectral interval with comparable vertical layering. With proper vectorization and parallel processing, FASCODE's speed can be greatly enhanced. However, MODTRAN's structure is equally vectorizable, so the ratio of improvement should ultimately be maintained.

Flux Calculation

The upwelling and downwelling fluxes of radiant energy at a given atmospheric level are calculated by integrating the radiance, $I_\nu(\mu)$, at wavenumber ν over the appropriate hemisphere,

$$F_\nu^{+}=\int_0^{2\pi}\int_0^{1} I_\nu(\mu)\,\mu\, d\mu\, d\phi$$

$$F_\nu^{-}=\int_0^{2\pi}\int_{-1}^{0} I_\nu(\mu)\,\mu\, d\mu\, d\phi$$

where μ is the zenith direction cosine and Φ is the azimuthal angle. In our case, it is assumed the radiances are azimuthally independent; therefore the integrals become

$$F_\nu^{\pm}=\pm 2\pi\int_0^{\pm 1} I_\nu(\mu)\,\mu\, d\mu\ .$$

The required integration for determining the upwelling and downwelling fluxes was computed using a standard two point, first moment Gaussian quadrature. Comparison of two point vs. three point quadrature did not show sufficient improvement to justify the additional time involved in the computation. When simultaneously plotted, the 2 angle and 3 angle cooling rate curves were nearly coincident. The direction cosine values, associated angles and quadrature weights are given in the following table:

Direction Cosine	Angle	Weight
0.3550510257	69.2034283	0.1819586183
0.8449489743	32.3335307	0.3180413817

Table 1: Gaussian quadrature angles and weights

MODTRAN2 was used to calculate the radiance along a path to space corresponding to each of the given angles at each defined atmospheric level. The downwelling flux was then found by the first moment quadrature. The upwelling flux resulted from integrating the radiances along paths corresponding to the complement of each given angle.

The net flux at any level was then calculated as the difference between the upwelling and downwelling fluxes.

$$F_v = F_v^{+} - F_v^{-}$$

Cooling Rate Calculation

The divergence of the net flux at atmospheric level ℓ represents the rate of energy loss per unit volume of atmosphere, or the cooling rate

$$Q_v = \Delta F_v .$$

The monochromatic cooling rate for the atmospheric layer bounded by levels ℓ and ℓ-1 is computed in terms of change in temperature, θ, with respect to time, τ, by the finite difference formula

$$\frac{\partial\theta}{\partial\tau}\Big|_{v;l,l-1} = \frac{g(F_{v;l} - F_{v;l-1})}{C_p(P_l - P_{l-1})}$$

where g is gravitational acceleration, C_p is the specific heat of air at constant pressure, and P is pressure. A value of 8.422 (mbar K d^{-1}) per (W m^{-2}) is used for the ratio $\frac{g}{C_p}$ as in *Ridgway et al.*, (1991), independent of altitude.

Comparison of Cooling Rate Results

All MODTRAN2 calculations were based on 60 atmospheric layers as defined by *Clough, et al.*, (1992). Layers were spaced at increments of approximately 20 mb pressure from 0 mb to 1013 mb. Cooling rates were found to be sensitive to the chosen layering at both the top and bottom of the defined atmosphere.

Data for layer temperatures and water vapor densities were interpolated from the published ICRCCM data in *Ellingson, et al.*, (1991).

The cooling rate results as compared to the published FASCODE results were very good. Agreement was within the 2% documented FASCODE - MODTRAN agreement in most regions. Relative errors in the net fluxes, mid-latitude summer atmosphere, were all less than 1% with the exception of the net flux in the ground layer which had the maximum relative error of 3.7%.

A comparison of cooling rate results for mid-latitude summer, tropical, and sub-arctic winter atmospheres is given in figures 1-3. Plots represent spectrally integrated cooling rates.

A representation of spectrally dependent cooling rates corresponding to published FASCODE results (*Clough, et. al.*, (1992)) is given in figure 4.

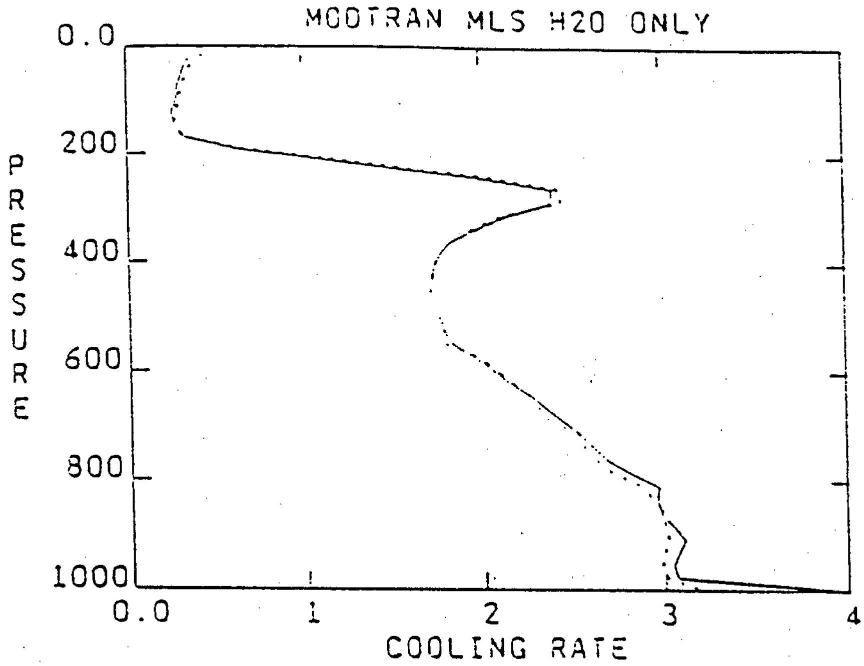


Figure 1: Comparison of spectrally integrated cooling rates: ICRCCM mid-latitude summer atmosphere, water vapor only. Solid line represents MODTRAN2 results and dashed line represents FASCODE results.

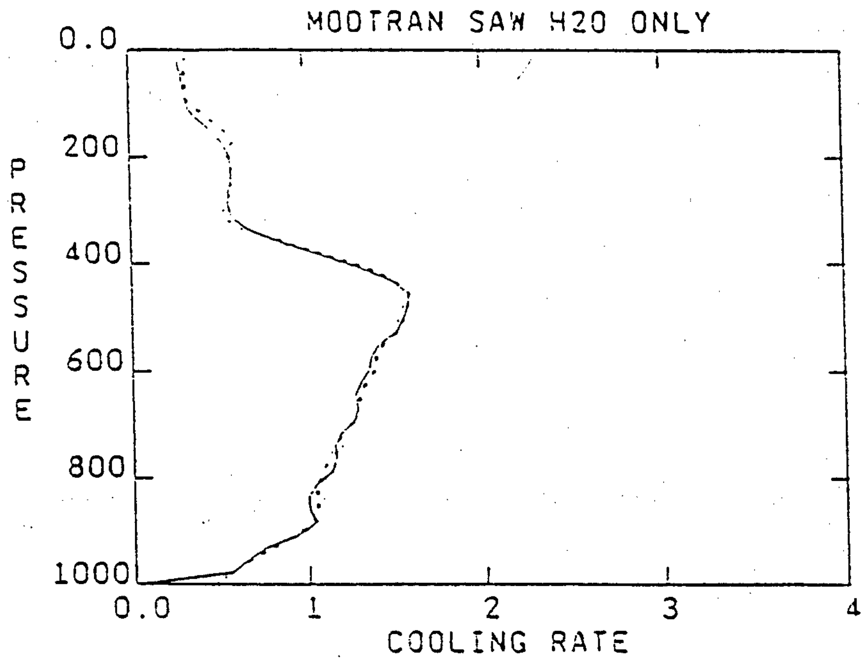


Figure 2: Comparison of spectrally integrated cooling rates: ICRCCM sub-arctic winter atmosphere, water vapor only. Solid line represents MODTRAN2 results and dashed line represents FASCODE results.

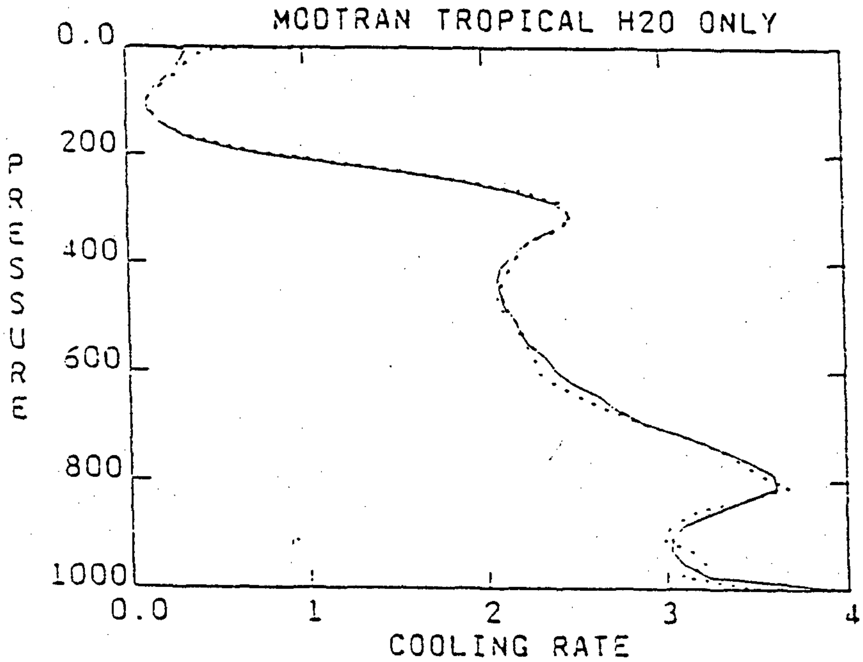
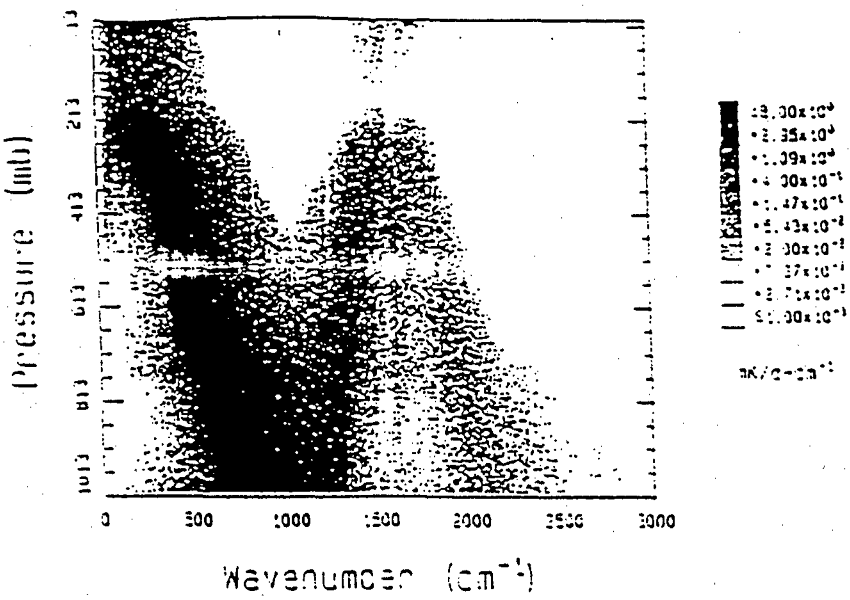


Figure 3: Comparison of spectrally integrated cooling rates: ICRCCM tropical atmosphere, water vapor only. Solid line represents MODTRAN2 results and dashed line represents FASCODE results.

MODTRAN ICRCCM MLS H_2O Only



MODTRAN ICRCCM MLS H_2O Only

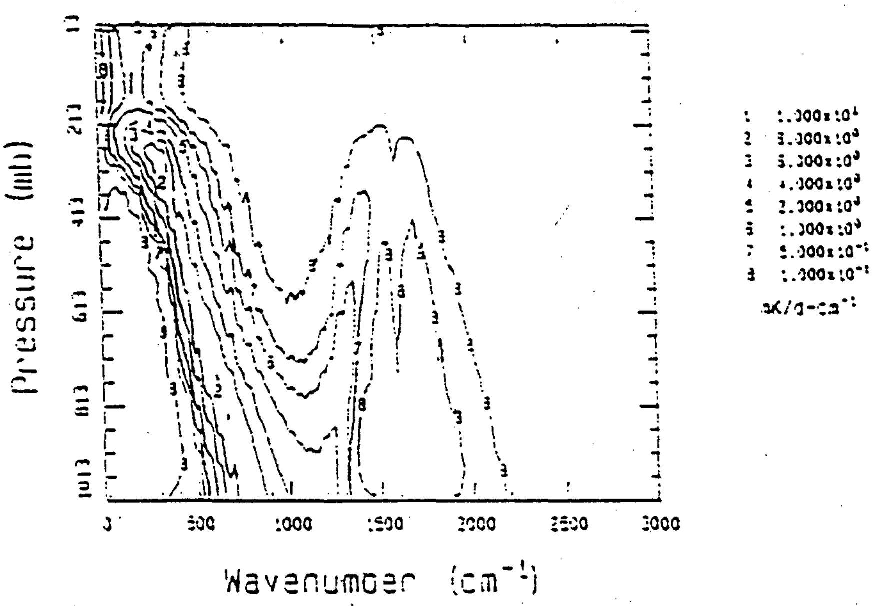


Figure 4: Spectral cooling rate profile for the ICRCCM mid-latitude summer atmosphere with water vapor only.

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